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Impact of start-up and shut-down losses on the economic benefit of an integrated hybrid solar cavity receiver and combustor

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HIGHLIGHTS

- We present the benefits of integrating a solar cavity receiver and a combustor.
- The hybrid solar receiver combustor is compared with its equivalent hybrid.
- The start-up losses of the back-up boiler are calculated for a variable resource.
- Levelized cost of electricity is reduced by up to 17%.
- Fuel consumption is reduced by up to 31%.

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ABSTRACT

The impact of avoiding the start-up and shut-down losses of a solar thermal power plant by directly integrating the back-up boiler into a tubular solar-only cavity receiver is studied using a multiple time-step, piecewise-continuous model. A steady-state analytical model of the mass and energy flows through both this device and a solar-only cavity receiver reported previously are incorporated within a model of the solar power generating plant with storage. The performance of the Hybrid Solar Receiver Combustor (HSRC) is compared with an equivalent reference conventional hybrid solar thermal system employing a solar-only cavity receiver and a back-up boiler. The model accounts for start-up and shut-down losses of the boiler, threshold losses of the solar-only cavity receiver and the amount of trace heating required to avoid cooling of the heat transfer fluid. The model is implemented for a 12 month/five year time-series of historical Direct Normal Irradiation (DNI) at 1 h time-steps to account for the variability in the solar resource at four sites spanning Australia and the USA. A method to optimize the size of the heliostat field is also reported, based on the dumped fraction of solar power from the heliostat field. The Levelized Cost of Electricity (LCOE) for the HSRC configuration was estimated to be reduced by up to 17% relative to the equivalent conventional hybrid solar thermal system depending on the cost of the fuel, the storage capacity and the solar resource, while the fuel consumption was estimated to be reduced by some 12–31%.

1. Introduction

The need to mitigate greenhouse gas emissions is driving the development of technologies to harness renewable energy sources such as solar and wind, which are abundant in nature [1]. However, these forms of energy are also diffuse and intermittent. Two of the potential solutions to manage cost effectively the intermittent nature of the renewable resources are storage technologies and hybrids with combustion technologies [2–4]. Of the various types of storage technologies, thermal energy storage (TES) is often the most desirable due to its high performance in energy storage density and energy conversion efficiency [5]. When coupled to a solar thermal plant, TES also allows electricity to be dispatched at times when the solar resource is unavailable. However, it is presently only cost-effective to address some of the variability this way [6], that is, it is unlikely to be economic to store enough energy to cover for periods of extended cloud [7]. Hybrids with fossil fuel systems are attractive in the short term because renewable energy provides a means to reduce CO_2 emissions, while fossil fuels inherently contain stored chemical energy readily available at a low cost [8]. For these reasons a combination of thermal energy storage and hybrid systems offers the potential to provide some CO_2 mitigation at moderate cost, together with a continuous electricity output [9]. In the longer term, the combustion source could be provided from

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Nomenclature

$\widetilde{C}$	concentration ratio
A	area (m^2)
I	solar irradiation (W/m^2)
Q	energy (J)
$\dot{Q}$	heat transfer rate (W)
$\dot{W}$	work rate = power output (W)

Greek symbols

σ	Stefan-Boltzmann constant
η	efficiency
χ	fraction

Abbreviations

CST	Concentrating Solar Thermal
DNI	Direct Normal Irradiation
EPGS	Electrical Power Generating System
HSRC	Hybrid Solar Receiver Combustor
IEA	International Energy Agency
LCOE	Levelized Cost of Electricity
PBR	Power Block Ratio
SGH	Solar Gas Hybrid
TES	Thermal Energy Storage

Subscripts

ap	aperture
boil	boiler
cap	capacity
comb	combustion
crit	critical or threshold value
dump	dumped
DN	Direct Normal
elec	electrical
exh	exhaust
gen	generator
helio	heliostat
min	minimum
noz	nozzle opening
rec	solar receiver
salt	molten salt
sec	secondary air
sol	solar
stm	steam
sto	storage
t	time (years)
th	thermal output
trace	trace heating
use	useful

biomass or other forms of low-carbon-intensive fuel. In light of this, there is a need for hybrid thermal energy systems to complement renewable energy sources.

One recently proposed hybrid technology concept utilising energy storage is the Hybrid Solar Receiver Combustor (HSRC), of Nathan et al. [10]. Their preliminary economic evaluation found that, relative to the nearest equivalent system with a separate solar-only cavity receiver and a boiler, termed the solar gas hybrid (SGH), the HSRC reduces the capital cost of the overall power system, which includes the storage tanks, steam generator, Electrical Power Generating System (EPGS) and backup boiler (for the SGH) system, by up to 18% and overall LCOE by up to 11% for a 100 MW_{th} receiver size [11]. However, that assessment was based only on annually averaged performance of the plant and did not consider the influence of the variability of the solar resource. Lim et al. has recently developed an analytical model consisting of heat transfer and energy balance equations, which can be used to model performance of the HSRC at each time-step in a data string of solar resource. That model was used to determine the dimensions of the HSRC required to achieve similar efficiencies to that of a solar-only cavity receiver and a conventional boiler, and to estimate the subsequent weight of the device relative to a solar-only device [12]. The assessment confirmed that configurations can be found for which the combustion-only model of the HSRC achieves similar performance to the stand-alone boiler for a weight that is approximately double that of a solar-only device, justifying a key assumption in the economic assessment of Nathan et al. [11]. However, the economic study by Nathan et al. also did not consider the further potential benefits associated with avoiding the start-up and shut-down losses of a boiler and the trace heating required to maintain the temperature of the working fluid (here molten salt) for the solar-only cavity receiver. In addition, the minimum threshold of solar flux required for the HSRC is expected to be lower than that of the SGH, the benefits of which was also not analysed in their assessment. Hence, there is a need to account for the effects of resource variability both on the actual differences in operation and on the influence of start-up and shut-down losses on the potential additional benefits of the integrated HSRC device over the SGH.

For a conventional SGH to be run continuously, it is necessary to operate the boiler in “stand-by” mode for periods. This requires maintaining the boiler at a sufficiently high temperature, and/or starting it up before the steam is needed, to allow the boiler to be brought on line when required during periods of low solar insolation. For this reason, both start-up and shut-down losses are incurred during the transitions between solar-only and combustion-only operation, which leads to additional fuel consumption. In addition, the rate at which the boiler can be heated up is limited by the thermal stresses on the walls of the boiler [13]. Hence, the heat-up time for a boiler is set by the manufacturer’s specification. Furthermore, the minimum capacity of a conventional boiler is also limited, with a typical turndown ratio of the maximum to minimum throughput being in the range of 3–4 [14]. The HSRC offers the potential to avoid most of these losses because it replaces the two units with a single device that is kept warm continuously by either Concentrating Solar Thermal (CST) or combustion. However, the magnitude of these potential benefits depends both on the start-up and shut-down requirements of the boiler and on the solar resource variability (seasonal, diurnal and weather-based), so that they can only be evaluated reliably by a model that accounts for all of these factors. Hence the present paper also aims to compare the influence of start-up and shut-down losses from the two types of hybrid system.

In a conventional SGH as with any solar power tower system, a trace-heating system is needed to maintain above its freezing point the temperature of the heat transfer fluid within the piping system [15,16]. The current state-of-the-art heat transfer fluid in solar thermal systems around in the world is molten salt, although other fluids are also being considered [17]. The need for electrical trace heating brings significant challenges. For example, non-uniform